Delayed Coastal Upwelling along the U.S. West Coast in 2005: A Historical Perspective

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Abstract. The timing of the onset of coastal upwelling in spring and its intensity over the upwelling season are critical factors in the productivity and structure of the California Current ecosystem (CCE). We use an index of coastal upwelling to characterize physical forcing over the latitudinal extent of the CCE, and compare the evolution of the upwelling season in 2005 with previous years. The onset of coastal upwelling in 2005 in the northern California Current was delayed by 2-3 months. Upwelling was stronger than normal in the latter part of the upwelling season, allowing the cumulative upwelling to reach the climatological mean by fall. Although physical conditions were unusual in 2005, they were not unprecedented in the historical record. However, the timing and strength of coastal upwelling is a critical ecological factor, particularly for species whose life histories are closely tuned to the annual cycle. The unusual physical and biological conditions observed in spring 2005 illustrate the sensitivity of the CCE to possible future climate extremes.

1. Introduction

During the past decade, the U.S. west coast has been affected by a series of strong climate forcing events, including an intense El Niño followed by a La Niña (Chavez et al., 2002a,b, Schwing et al. 2002), with the latter accompanied by a marked cooling of the upper ocean along the coast (Bond et al., 2003; Peterson and Schwing, 2003), and a 2002 intrusion of subarctic waters (Freeland et al., 2003). A striking attribute of each of these events was the rapid and strong ecosystem response in the California Current to changes in physical conditions. The decline in lower trophic productivity during the 1997-98 El Niño was followed by a rapid expansion of productive habitat during the subsequent La Niña (Bograd and Lynn, 2001; Kahru and Mitchell, 2000). The intrusion of nutrient-rich subarctic waters resulted in high production and respiration, resulting in an anoxic event on the Oregon continental shelf in summer 2002 (Grantham et al., 2004). On a larger scale, the California Current ecosystem (CCE) has seen higher overall productivity and reorganized species assemblages associated with an extended cool phase after 1998 that some suggest may represent a new climate regime (Bond et al., 2003; Peterson and Schwing, 2003).

In the spring and summer of 2005, unusual conditions again prevailed in the CCE, with anomalously warm sea surface temperatures (SST; Strub et al., 2006), low chlorophyll levels (Thomas and Brickley, 2006), a spatial redistribution of zooplankton species (Mackas et al., 2006), record low rockfish recruitment and a lack of forage species (Brodeur et al., 2006), and the breeding failure of a dominant planktivorous marine bird, the Cassin's auklet (*Ptychoramphus aleuticus*) (Sydeman et al., 2006), off central California. Here we characterize the large-scale atmospheric forcing and oceanic response that contributed to these ecosystem responses. We use an index of coastal upwelling to characterize physical forcing over the latitudinal extent of the CCE, and to compare the evolution of the upwelling season in 2005 to that from previous years. Although the physical conditions were unusual in 2005, they were not unprecedented in the historical record. However, the delayed onset of upwelling was a critical factor to ecosystem productivity.

2. Data and Methods

Coastal upwelling is the dominant process leading to high productivity and species diversity in the CCE (Huyer, 1983). Both the timing of the onset of coastal upwelling in spring (Cushing, 1990; Beare and McKenzie, 1999; Bograd et al., 2002) and its intensity over the upwelling season have critical impacts on the overall productivity and structure of the ecosystem. Many marine populations have evolved life history strategies that take advantage of the annual upwelling cycle, so deviations in this cycle are likely to have discernable ecosystem effects.

Upwelling indices were derived from the 6-hourly sea level pressure (SLP) fields from the US Navy Fleet Numerical Meteorology and Oceanography Center (Bakun, 1973; Schwing et al., 1996) Since upwelling has a cumulative effect on ecosystem productivity and structure, we computed a cumulative upwelling index (CUI) based on integrating the mean daily upwelling indices at six locations in the CCE, from 33°N to 48°N, separated by 3° latitude. The climatological mean (1967-2005) CUI was computed at each latitude, yielding a mean start and end date of the upwelling season (Figure 1). Annual CUI series at each location were then computed for each year between 1967-

2005, with the integration beginning at the climatological onset (when the mean UI is initially positive) and ending at the climatological end of the upwelling season. To compare the CUI over the extent of the CCE and over time, we compute an annual normalized CUI anomaly (CUIA) for the date of maximum mean upwelling (defined as the maximum slope of the climatological CUI) at each location. The CUIA is the difference between the annual and the climatological mean CUI for that date, normalized by the standard deviation of the CUI for that date. The date of maximum mean upwelling, and the mean (and standard deviation) strength of the CUI for that date are given in Figure 1.

3. Patterns of Coastal Upwelling in the CCE

The climatological CUI series separate the CCE into two distinct regions divided near Cape Mendocino (~40°N; cf. Parrish et al., 2000). South of Cape Mendocino, the large-scale winds are upwelling favorable nearly year-round, while the upwelling season off Oregon and Washington is typically only 150-200 d long (Figure 1). The timing and strength of peak upwelling also differs north and south of Cape Mendocino. Upwelling peaks in early June (Julian Day 159-167) in the southern CCE, while upwelling in the northern CCE does not usually begin until April and peaks, more weakly than in the south, in July (JD195-204; Figure 1).

The 2005 CUIs and their anomalies also show a clear regional signal (Figure 1). Upwelling was weak throughout the CCE in 2005, with the greatest deviation in the north. The CUI at 33-39°N were near their respective climatologies until the date of mean peak upwelling, after which upwelling was anomalously weak. Off Oregon and

Washington, however, persistent upwelling did not commence until late June, and was anomalously weak through July, leading to anomalously low CUIs for much of 2005. At the time when the peak in seasonal upwelling was expected, the CUIA was strongly negative in the northern CCE (Figure 1, Figure 2). In general, the 2005 upwelling season in the northern CCE had one of the most delayed onsets in the 40-year record (Figure 2). Upwelling was stronger than normal during the latter part of the upwelling season, allowing the CUI for 2005 to reach the climatological mean by fall.

Although the 2005 upwelling season in the north was unusual compared to the long-term climatology, it was not unprecedented in terms of its timing or strength (Figure 1, Figure 2). A number of previous years displayed a similar pattern, particularly 1983, 1986, 1988, 1993, and 1997 (Figure 2, Table 1). Three of these years (1983, 1986, 1993) featured tropical El Niño events, while the other two (like 2005) did not. On the other hand, the five years most unlike 2005 (1967, 1968, 1970, 1982, and 1999) were characterized by strongly positive CUIA over portions of the CCE (Figure 2). There also appear to be long-term trends in the timing and strength of upwelling within the central CCE; the late 1960s through late 1970s were characterized by positive upwelling anomalies, while 1980-1995 saw generally negative CUIAs (Figure 2). Persistently strong upwelling occurred in 1999-2002 in the central CCE (Figure 2; Schwing and Moore, 2000), followed by weaker upwelling since 2002. The northern and southern extremes of the CCE have displayed a less consistent pattern of upwelling over the 40-year period. Using a SLP-based index extending back to 1899 (Trenberth and Paolino, 1980), 2005 stands out as the seventh weakest upwelling year (not shown).

4. Patterns of Large-Scale Atmospheric Forcing

We next examine how the large-scale atmospheric circulation relates to coastal upwelling by comparing 2005 with past years featuring anomalous upwelling along the coast. The atmospheric circulation during 2005 is summarized in terms of the anomalous SLP for April-June over the North Pacific (Figure 3a); the canonical pattern in SLP associated with anomalous upwelling in the region of interest (roughly Cape Mendocino to the northwest tip of Washington state) is constructed by regressing gridded values of North Pacific SLP against the average of the upwelling indices at 42°N, 45°N, and 48°N, for the period 1946-2005 (Figure 3b). The distribution of anomalous SLP during 2005 resembles the canonical pattern in that both indicate centers near 45°N, 130°W. SLP variability in this region in 2005 and in past events was largely determined by the cross-shore pressure gradient and hence the meridional (upwelling) component of the seasonal mean winds along the coast. On the other hand, during 2005 a stronger anomalous low was centered near 45°N and the dateline, while the canonical SLP pattern is not anomalous in the region. This difference suggests that the teleconnections between the anomalous SLP and winds along the west coast and other elements of the North Pacific climate system on the basin scale may not be robust.

To illustrate this last point, we have considered how 2005 compares with the five previous weakest (and strongest) upwelling springs in terms of a small number of indices that have been used previously to characterize large-scale aspects of the North Pacific climate system. The values of these indices (April-June averages), and their corresponding normalized CUIA, are itemized in Table 1. For the most part, weak (strong) upwelling events tend to occur during warm (cool) ENSO conditions, as signified by the NINO3.4 index, positive (negative) states in the Pacific Decadal Oscillation (PDO), Pacific-North American (PNA) and the East Pacific-North Pacific (EP-NP) modes, and negative (positive) states in the Northern Oscillation Index (NOI). However there is not a persistently strong relationship between upwelling and these large-scale indices. Especially weak upwelling occurred in 1986 and 1988, even though ENSO was in a near-neutral and cool phase, respectively. Similarly, the PDO was only moderately positive in 1988 during the weakest upwelling since 1967. The strong upwelling events also include exceptions. For example, the NINO3.4 index was positive during spring 1982. These results indicate that coastal upwelling and the North Pacific climate system is a complex response to local and remote forcing, including but not limited to ENSO.

5. Discussion and Conclusions

The delayed onset of coastal upwelling in the northern CCE created a significant perturbation in ocean conditions and the marine ecosystem, particularly for populations dependent on upwelling early in the climatological upwelling season that coincides with their reproductive cycles. Some populations, particularly in the northern portion of the CCE (e.g., central California seabirds and rockfish, and Oregon zooplankton) were substantially impacted by the weak and delayed upwelling (Brodeur et al., 2006; Sydeman et al., 2006). Others appear to have been minimally affected by the unusual conditions. Populations off southern California experienced near-normal upwelling through the first half of 2005 and, in general, did well (S.V. Ralston, pers. comm..). Despite relatively normal upwelling off central California, however, some populations in this area were particularly impacted. Perhaps this indicates that delayed and weak upwelling “upstream” of this region influenced productivity or food availability negatively for seabirds and rockfish. Anomalously weak equatorward transport in winter and spring prior to the 2005 upwelling season may have pre-conditioned the system for lower production (Strub et al., 2006). It is also necessary to consider how ecological “pre-conditioning”, such as starvation conditions prior to 2005, may have contributed to reproduction.

The behavior of individual species may have determined their sensitivity to this event. We emphasize that the delayed timing of upwelling, rather than the cumulative amount, appears to be the critical ecological factor, suggest that species whose reproduction is closely tied to the seasonal cycle were impacted severely by the delayed upwelling, while those with a more flexible life history strategy were relatively more successful. We also speculate that populations whose feeding strategies are limited to near-surface, near-coastal waters were more vulnerable than deeper and wider ranging feeders. Finally, once upwelling commenced in earnest in late July, SSTs quickly cooled to normal values in the northern CCE, suggesting that the total primary production over the course of the season was near normal. Thus demersal species may not have been strongly impacted by the unusual upwelling conditions in 2005.

Coastal upwelling in the northern CCE in 2005 was unusual but not unprecedented. The 2005 CUI was similar to some past El Niño events, but the large-scale forcing was not predominantly tropical. Large-scale atmospheric forcing (e.g., jet stream position, teleconnections) is important in establishing the conditions that initiate and drive upwelling, but regional atmospheric forcing associated with the position, strength and timing of the North Pacific High and, to a lesser extent, the Southwestern US Low, may determine upwelling in the CCE. One important conclusion from this study is that tropical El Niño events may lead to unusually weak west coast upwelling, but these are not its sole cause. Other sources of atmospheric forcing anomalies can lead to delayed or weak upwelling in the CCE.

Pierce et al. (2006) found a strong relationship between cumulative upwelling and upper ocean structure off Oregon, which creates a bottom-up perturbation through the ecosystem (Barth et al., 2006). However, other factors affect the effectiveness of coastal upwelling to ocean productivity. Offshore transport, water column stability, and freshwater input are factors in west coast primary productivity (Ware and Thomson 2005). Variability in these processes may have contributed to the unusually poor production in 2005. Belated seasonal upwelling, such as noted in 2005, is less efficient at uplifting nutrients, due to stronger vertical stratification in summer (Kosro et al. 2006). Hickey et al. (2006) credit the anomalous conditions to local and remote wind forcing along with changes in the source water and its alongshore advection prior to upwelling.

These observations demonstrate the critical importance of anomalous upwelling to the CC ecosystem, not only in terms of its strength, but in its timing and seasonal evolution. Did past years that were similar to (different than) 2005 have similar bad (good) ecosystem responses? Based on the inferred mechanisms for the unusual upwelling and its dramatic ecological consequences, namely the delayed spring transition, 2005 could be an analog for a global warming scenario (cf. Snyder et al. 2003; Diffenbaugh et al. 2004). We cannot determine if 2005, or any individual year, is part of a new climate regime, or a consequence of climate variability or global change. Our results also do not conclusively demonstrate global warming or a link between it and ecosystem change. However, anomalous years are useful in determining the sensitivity of ecosystems to possible future climate extremes. Within the context of climate projections, they provide observations for validating coupled physical-biological models and the likely impacts to coastal-upwelling ecosystems should projections of future climate change prove correct. As regional climate model projections improve, and our understanding of the linkages between climate variability and marine ecosystem response increases, we will be able to answer this question with greater confidence.

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Table 1. Spring (April-June mean) magnitude of large-scale Pacific climate indices for 2005, and for the 5 years with most negative and most positive CUIA over the period 1967-2005. Extreme years based on value of normalized CUIA on the date of maximum mean upwelling, averaged over 42-48°N.

Year	CUIA	NIÑO3.4	NOI	PDO	EP-NP	PNA
2005	-1.41	0.45	-0.08	1.35	0.80	1.10
1983	-0.90	1.03	-0.73	2.01	0.07	1.00
1986	-0.90	-0.11	0.11	1.20	-0.67	0.10
1988	-1.98	-1.01	-0.37	0.96	-0.67	1.03
1993	-1.54	0.92	-1.50	1.89	0.90	1.57
1997	-1.78	0.88	-1.39	1.88	1.47	0.37
1967	1.65	-0.28	-0.01	-1.10	1.17	-1.03
1968	0.87	-0.29	0.90	-0.64	-0.47	-0.30
1970	0.92	-0.01	1.00	0.00	-0.37	-0.33
1982	0.77	0.78	-1.17	-0.52	-0.57	-0.23
1999	1.03	-0.84	0.98	-0.80	-0.60	0.17

Figure Captions

Figure 1. Cumulative upwelling index (CUI; m^3 s^{-1} 100 m^{-1}) for six locations in the California Current. Integration was performed over the climatological upwelling season at each latitude, and arrows mark the time of maximum climatological upwelling at each latitude. Julian days of start (SD) and end (ED) of upwelling season and maximum upwelling (MD) are shown for each location. Mean and standard deviation (black solid and dashed curves, respectively), 1967-2004 individual years (gray curves), and 2005 (red curve) are shown.

Figure 2. Time series of normalized cumulative upwelling index anomalies for the date of maximum climatological upwelling (CUIA) at each latitude. Red (blue) denotes stronger and/or earlier (weaker and/or later) upwelling.

Figure 3. (a) April-May-June SST (shade) and SLP (contour) anomalies regressed onto the upwelling index, scaled by the 2005 upwelling index value (-27 m^3s^{-1}100 m^{-1}), and (b) same, but 2005 anomalies (1967-2005 climatology). Contour interval 1 hPa, with thick zero and dashed negative. SST is the Met Office Hadley Centre's sea ice and sea surface temperature (SST) data set at 1-degree latitude-longitude resolution (Rayner et al. 2003), and SLP is the NCEP - NCAR reanalysis (Kistler et al. 2001) at 2.5-degree latitude-longitude resolution.

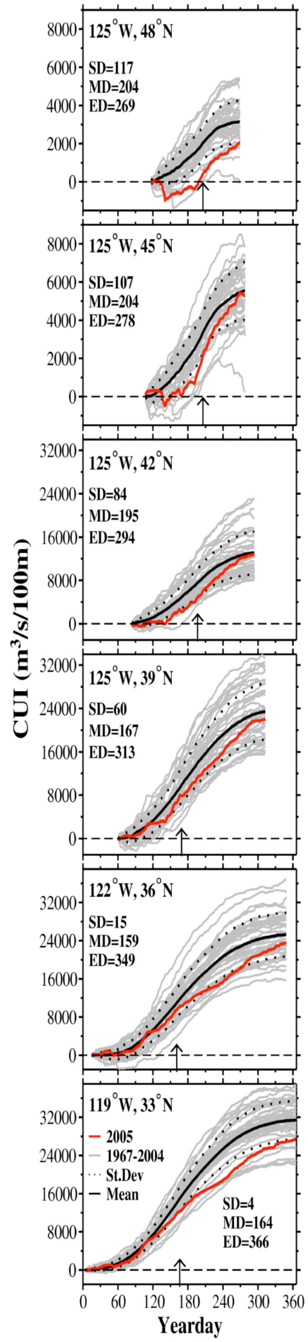
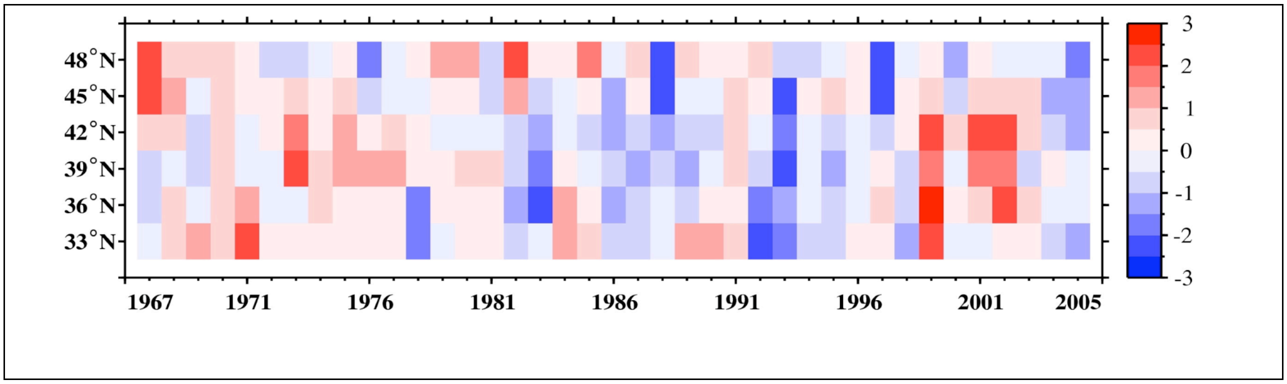

125°W, 48°N
SD=117
MD=204
ED=269
125°W, 45°N
SD=107
MD=204
ED=278
125°W, 42°N
SD=84
MD=195
ED=294
125°W, 39°N
SD=60
MD=167
ED=313
122°W, 36°N
SD=15
MD=159
ED=349
119°W, 33°N
2005
1967-2004
St.Dev
Mean
SD=4
MD=164
ED=366
CUI (m³/s/100m)
Yearday

Figure 1


48°N
45°N
42°N
39°N
36°N
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1967
1971
1976
1981
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1
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-1
-2
-3

Figure 2

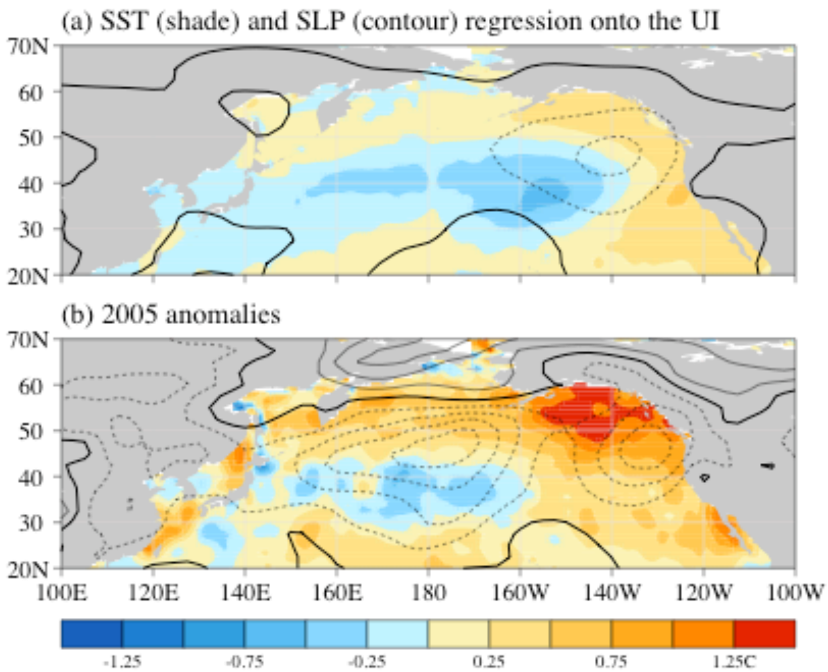
(a) SST (shade) and SLP (contour) regression onto the UI
70N
60
50
40
30
20N
(b) 2005 anomalies
70N
60
50
40
30
20N
100E
120E
140E
160E
180
160W
140W
120W
100W
-1.25
-0.75
-0.25
0.25
0.75
1.25C

Figure 3